6/5/98

Voltage, Current, Torque, Speed Mode of Operation, Stability
What's it all about?

Throughout my career, the most often asked questions seem to focus on motors, the types available, and their modes of operation. Questions dealing with the advantages and disadvantages of being particular operating modes and how to determine which of the available motor types is most suitable for a given application constantly arise. In this report I hope to clear up some of the misconceptions about motor/amplifier packages, operational modes, mode terminology, and general benefits.

In addition to properly selecting a motor type such as brush, brushless, stepper, etc., and its operating mode such as voltage, current, torque, etc., the ability to tune a motion controller's gain algorithm will also work better with the proper motor/amplifier selection. This little considered fact can go a long way in ***helping*** you finish the job, rather than fighting it!

A person does not have to know how to design a motor or amplifier in order to understand the basic laws and principals that govern them. But we must understand those laws and principles in order to properly select and apply motors and their amplifiers. Within the magic of motion control it is the person who has a clear understanding of the problems who will make the application succeed.

The idea, then, is to reduce the principals of motor/amplifier operation down to a few simple ones to reduce design complexity. There is an excellent series of articles being written by Dick Welsh, of Welsh Enterprises, detailing motor design issues such as the effect of motor resistance on motor efficiency, RMS and peak thermal calculations, and other general motor design criteria. But that's not the purpose of this article. The purpose of this article is to present a simple method for fitting a motor to an application by understanding a few simple motor principles.

Stability and Motor Design

To start at the beginning, we must actually start at the end . . . the motor. Without being motor designers, there should be some obvious facts about a motors operation which can point us in the proper direction selecting a motor for a given application. In addition, they should also allow us to determine what mode the motor should be operated in.

The principles we need to understand are simple:

1. It is the magnetic field within the motor that develops motor torque.
2. The magnetic field between the motor armature and stator must appear to rotate in order to make the armature move (commutation).
3. It is the current injected into the motor windings which develops the magnetic field

4. The current within the motor windings is limited only by the terminal voltage applied to the motor (assuming the wires do not melt).
5. The speed of the motor is a function of the voltage available or commutation frequency

From this, the issue of motor stability can be presented. To be stable is to imply constant motion (i.e. moving or stopped). Thus, for a motor to be stable while rotating the stator's moving magnetic field must not change in intensity, or contain any discontinuities during rotation. But since a motor is constructed with wound coils (poles), magnet materials, air gaps, bearings, laminations, etc., it would also be correct to say that if the motor is round, it is close to, but not necessarily mechanically symmetrical through the full 360 degrees of its rotation. That means if the spacing between poles is not exactly the same (+/-0 tolerance), there would be inconsistency in the motion, and thus present a stability issue. The one thing about rotary motors is that all errors produced are recovered every 360-degrees of rotation. In the case of linear motors, motion errors are accumulated, and stability becomes more expensive.

In addition to inconsistencies in mechanical design, the motors magnetic field, which is produced by the current in the motors windings, is done so by virtue of analog development. That is, the motor current is controlled by application of a terminal voltage produced by a motor amplifier via a power supply which is fed by some finite line voltage. Any variation in any of these systems will create motion instability. Thus, if it is necessary to run or hold absolute velocity or position with minimum jitter, a linear (analog) vs. chopped (PWM) amplifier should be utilized. Most all motor amplifiers come in these two styles. In addition, as the motion controller tries to move the motor it would be important for the rotary or linear motor to have a relatively low amount of friction. With low friction, the force required to start a move and the force trying to prematurely stop a move (friction) will be reduced with a subsequent increase in stability.

If we think about a stepper motor that has 200 full steps per revolution, each step being worth 1.8 degrees of rotation, it will take more power to move this motor one step than it would a motor that has 500 (full) steps per revolution (0.72 degrees). It, therefore, is easy to see that distance, power and stability all interact when using a stepper motor. The larger the distance jump to be made, the more power the device will require and the more instability it will have. This is true for the servo as well. But instead of steps (or detents) as we think of them in the stepper, they are encoder counts, gain structures and commutation algorithms. The controller wants to move a number of encoder counts in a prescribed amount of time. The more steps it needs to take, the more power it needs to have in the same given time interval.

In essence, the secret to smooth motion . . . up to this point . . . is low friction, analog current, high count commutation steps or poles, high stability of the analog electronics producing the voltage and current that drives the motor, and a high degree of mechanical precision in the construction of the motor. But the cost of stability cannot overshadow good engineering design. Instability in a motor can generally be overcome by, mapping the motor rotation and developing a software algorithm to control it, or in some cases, use of appropriate gearing. Thus, to reduce a 1% instability to 0.1% a 10:1 gear box might be useable.

Motor/Amplifier Modes

One step back from the motor is the motor amplifier. A motor amplifier generally has the following modes of operation, current and voltage. These modes are simple to understand but will produce several other modes of operation . . .

1. Current Mode:
   When set to current mode, a control signal input will develop a current output. This is absolutely the same principle that is used in a constant current power supply. Assume we want only one amp to flow into the motor. We apply the appropriate input signal to the amplifier to produce one amp into the motor. If the motor load changes, the motor will possibly speed up or slow down and the controller will adjust the amplifier output to change the motors terminal voltage to maintain exactly one amp into the motor. This could be the operation used by a Tension Control system with a DC motor.

2. Voltage Mode:
   When set to voltage mode, a control signal will develop a terminal voltage output to motor based on an analog tachometer signal or other velocity measurement signal. This is absolutely the same principle that is used in a constant voltage power supply. But note that only a voltage is applied to the motor. If the motor is not moving then no current is required and the voltage can go to zero. As the motor begins to turn, and continues to speed up, it will generate a Back-EMF which will subtract from the applied terminal voltage. Because the effective terminal voltage is reduced, the current in the motor will also the reduced. So to continue to rotate, the motor voltage must increase.

3. Velocity Mode:
   In the ***True*** velocity mode, position coordination required. Position will be known by checking acceleration, motion and deceleration of the motor via an encoders counts and a time interval.

   Thus, if the motor is held back, for whatever reason, and then be released, it will do one of two things . . . either simply recover to the speed assigned without over speeding, or over-speed to catch up to where it would have been had not been held back.

The model that controls the action of the current in a motor is called the ***motor formula:***

Im = (Et-Ebemf) / R

where:
Im = Motor current
Et = Motor Terminal (applied) Voltage
Ebemf = Motor Generated Back-EMF
R = Motor resistance in Ohms

Note that the response of the motor is based on the terminal voltage. Also notice that the power applied to the motor is automatically reduced as the motor speeds up due to the increase in the motors Back-EMF. The current will reduce until the motor reaches a speed approximately equal to the percentage of its terminal voltage with respect to its maximum voltage capability. In other words, if the DC motor requires 100 terminal volts for full speed operation, and only 50 volts is applied, the motor would run at 50 percent of its maximum speed.

But note that when in the current mode, the only limitation to the motors speed, once the torque required to break friction has been exceeded, is windage, viscus damping, friction, and other speed related items. In other words, if in our DC motor example, it required 1.0 amp to break friction, and 0.1 amp to override any limit due to viscus forces, and we apply 1.11 amp to the motor windings, then the motor would continue to accelerate to its top motor speed even if it only took ***one volt*** to produce that 1.11 amps! The result of this phenomenon is that by using the current mode, you can increase the bandwidth of your system.

Since all motors have a torque constant (Kt) associated with them, by applying a constant current we can obtain a constant torque. Thus, a new term can be associated with the current mode of motor operation, and that is, torque mode.

If an application were required to operate a motor at one or more speeds, and we wanted to maintain a low-cost solution with reasonable stability, the Voltage Mode would be my first choice. Then, by adding a tachometer to the motor amplifier package, less than 1% velocity stability can be achieved. If, however, I needed a tensioning device, then Torque mode would be suitable. This would be obtained by simply operating the motor in the reverse direction to the motion of the load with a constant current for applying a tension to the load. The motor in a tension application although not rotating, would not overheat as long as we keep the applied current under the continuous rated RMS current requirement.

Motion Controller Modes

The motion controller is slightly different than the motor amplifier. The motion controller can operate in position mode, standard velocity mode, true velocity mode, and torque mode.

To begin with, a motion controller contains a path generator. The path generator is nothing more than a mathematical calculation that determines where the system should be at any given time. This generator is referred to a trajectory or profile generator. But no matter what you call it, it is simply the mechanism that calculates the motion path which the motor must follow.

The trajectory generator will calculate position, acceleration, velocity and deceleration as a function of time on what the user has programmed the motion to do.

1. **Position Mode:** The position mode uses encoder position information (counts) to calculate and maintain motor coordination. When in the position mode, the

motion controller will control the motor amplifier, which can be operating in either the current or voltage mode. The position mode calculations will coordinate the actual motors position and speed to the user's requirement. There is also a target position to which it will decelerate to and stop at in one smooth motion.

Note, however, that the motor will try to achieve maximum speed when operating in the current mode once friction torque has been exceeded. Therefore, the relationship between the system time constant and the motion control update time should be at least 15:1.

2. **Standard Velocity Mode:** This mode is similar to the position mode, described above, except that there is no ending or target position assigned. In addition, like the position mode, if the motor is held back while the trajectory generator is operating, the motor will ***over speed trying*** to catch up to the position it should be in once released.

   However, like the position mode, the motor will try to achieve maximum speed when operating in the current mode once the friction torque has been exceeded. Therefore, the relationship between the system time constant and the motion control update time should be at least 15:1 as well.

3. **True velocity mode:** In this mode, position can be tracked, but it's not part of the move algorithm. Thus if the motor is held back, for whatever reason, and then released, it will simply recover to the speed assigned to it without over speeding.

   Note however, that like the position and standard velocity modes, the motor will try to achieve maximum speed when operating in the current mode once the friction torques have been exceeded. Therefore, the relationship between the system time constant and the motion control update time should also be at least 15:1.

4. **Torque Mode:** The torque mode is designed as a non-feedback current controlled system. That is to say, on command, a voltage will be written out of the motion controllers signal port, and will not change until a new value is written. There is no feedback involved, other than the users desire to adjust the output current value.

   Although this is considered a torque mode, if a voltage amplifier were used, this would simply replicate a potentiometer speed control and would then be considered operating in the Velocity Mode.

Advantages,   Disadvantages and Uses

To be fully functional, we need to do more than simply describe the differences between the various Modes.   We need to understand where these modes ***fit*** best.   They need to have certain capabilities if they are to be of value, otherwise they're just modes and don't really have anything to offer.

Since the bandwidth of the Current Mode is higher than for the same motor amplifier combination used in the Voltage mode, a good place for Current Mode operation is in high bandwidth/performance systems, such as labeling, stamping, flying-cutoffs, registration, etc. Also, since the motion controller is ***directly*** controlling motor current, ***zero*** following error is achievable using simple PID or other gain structure capable of running with zero following error.

On the other hand, the Voltage mode is excellent for short high speed move applications and in low RPM motion situations where there is not enough following error available to produce the required motion as if the system were in Current Mode. Voltage Mode helps stabilize the up/down handling of vertical loads and prevents dropping the vertical load in the event the controller output voltage goes to zero. By adjusting the sensitivity of the motor amp in the Voltage Mode, the effects of friction can be reduced since the amplifier will take over insuring the motor is always in motion.   This frees up the motion controller to concentrate on the positioning requirements.

Going back to Current mode operation, I have many times reduced gain values to ***soften*** the action of a servo motor which needs to have its load touch other load materials while at speed. The idea is not to have either of the loads overpower the other while they are in contact.   For example, when cutting extruded material chordal action of a conveyor chain can sometimes come into play.   Chordal action is the phenomenon occurring when a sprocket engages a chain at the top of an arc at which point, the chain is driven to full forward velocity.   As the sprocket turns, the chain link moves around the gears circumference reducing its forward velocity (producing a sinewave deceleration) until the next chain link engages the next gear sprocket.   This oscillation may also require the motor to keep up with the material while the chain forward motion is changing.   If the oscillation is not properly tracked, the material being handled could be badly stressed or damaged.

The Torque mode also works well whith discharge welding. In a capacitive discharge system, when arc has fired, it is required to ***plunge*** the part to be welded back into the molten puddle to a pressure, and held for a period of time.   Moving the parts together in the Torque Mode solves the problem of needing both high-speed once the arc is drawn, and having the appropriate pressure applied to the two parts simultaneously.

In the case of a multi-axis robot, the Voltage Mode might be more suitable for assisting the controller in offsetting the effects of gravity as the robot arms change their attitude with respect to the Earth (horizontal).

External Sinusoidal Commutation

In addition to motor operating modes, which generally pertains to the two basic styles of motor/amplifier operation and the three basic styles of motion controller operation previously discussed, there is another style of motor current control called "Sinusoidal Commutation." Sinusoidal Commutation (SC) is the art of controlling current delivered to the motor via the ***motion control computer***, rather than the motor amplifier. When using SC, the motors amplifier simply acts as a power interface between the low voltage current command, and the actual (high power) current applied to motor. The reason for using SC is twofold.

First, Sinusoidal Commutation can decrease the motor current step size (a torque surging, stability issue) by increasing the resolution of the device which is being used to signal when the motor current needs to be changed (commutated). The smaller the change in armature current (step size) at any time, the smaller the magnetic field change needed, and the smaller the power surge. In-other-words improved stability.

Second, with the increase in development of linear motors, it becomes a costly affair to have a Hall or Resolver type feedback units embedded into the linear motor pole structure. Since a linear motor already requires the use of a linear position measurement device, it only makes sense to try and use that device to also generate the commutation points for motor current.

The principle behind SC is to simply take the circuitry that converts the analog or PWM speed control signals to motor current commands out of the drive, and allow the motion controller to develop those speed control signals. The motion controller gain algorithm can be designed to immediately ***know*** the pole angle of the motor, and to develop the two or three phases of analog or PWM signals used for motor current commutation. The amplifier then becomes a simple power interface, but should still employ all of the safety devices found in any other amplifier, such as RMS and Peak current limit adjustments, +/-Limits, etc.

Conclusion

Motion control can be an elusive critter, allowing 20 engineers to wind up with 60 different answers . . . all of which, by the way, which can be right. The problem is really in picking the most cost effective, reliable, time efficient long term solution that will make the customer happy, and put profit in your pocket. Not an easy task considering the speed at which technology is changing. The best we can do is ***network*** along with our effort to read, research, and devise methods that work for us.

Chuck Raskin P.E. 6-Sigma, CMCS
Systems Engineer
Technology 80 Inc.